Dynamics of the Electron Density Profile and Plasma Turbulence during the L-H transition and ELMs in TEXTOR

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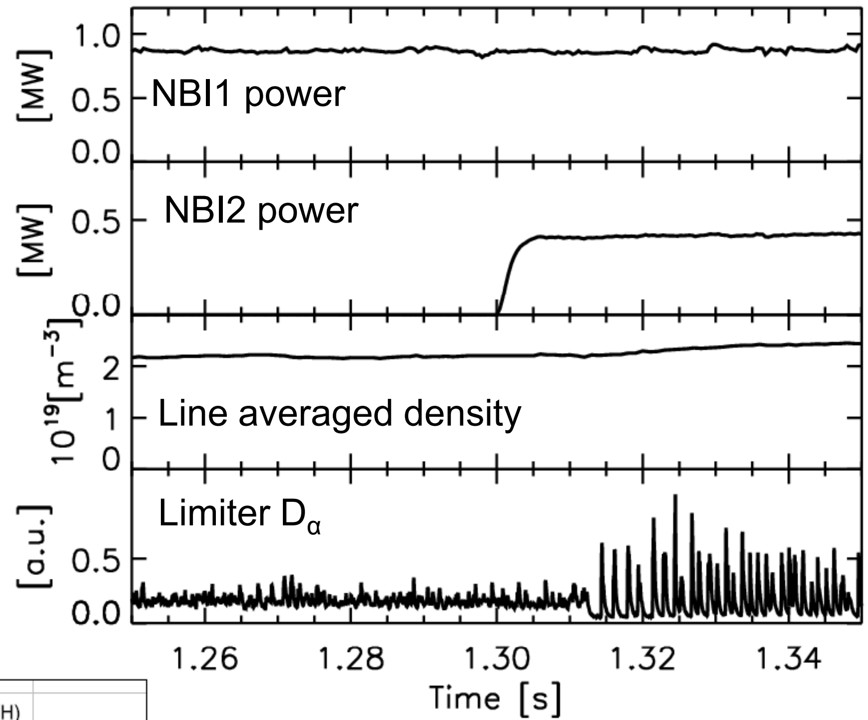
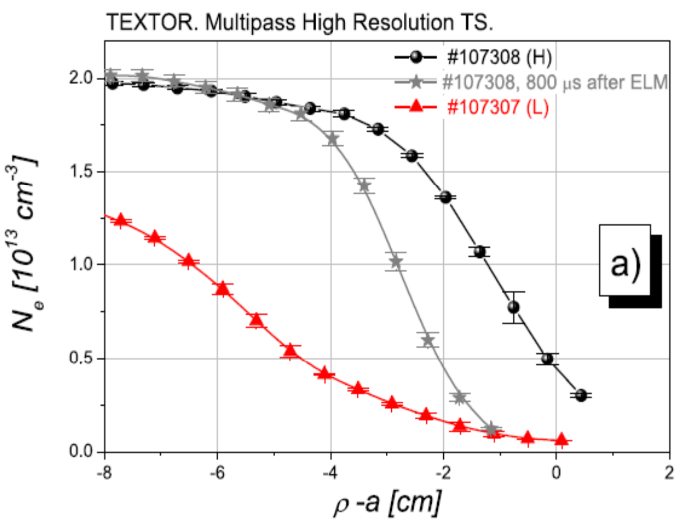
Limiter H-mode discharges can be achieved on TEXTOR under certain conditions:

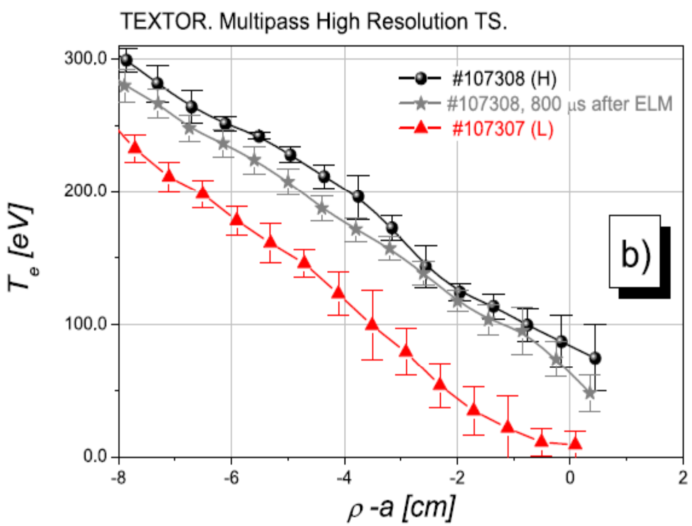
- Plasma shifted 3 cm to HFS
- 1 or 2 NBI heating (1.3 MW-2.6 MW)
- I_p=230 kA, B_t=1.3 T, $n_e(0)$ = 2-3 10^{19} m^{-3}



Features of H-mode:

- Significantly higher P_{LH} than divertor machines
- ~35% improvement in stored energy
- Pedestal only in the density
- 0.5-1 kHz ELMs (likely type III)





Pedestal density and temperature profiles in L and H-mode

*S. Soldatov, et al, PPCF **52** 085001 (2010)*

Although the TEXTOR H-mode might not be directly relevant for divertor tokamak scenarios, detailed studies might serve for benchmarking codes and theories.

The main diagnostic used in this analysis is the fast Li-BES system.

(Rebuilt by Wigner RCP, former KFKI RMKI)

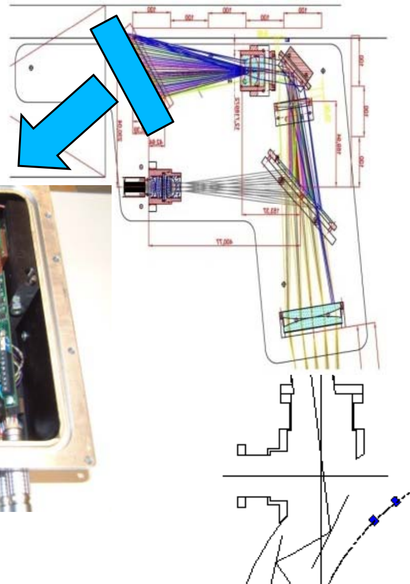
Standard 35 kV/1.3 mA Li-beam, 1.5 cm diameter

- Beam penetration from SOL to r/a 0.8-0.9
- ~2 cm radial smearing due to Li atomic physics, 1 cm radial channel separation

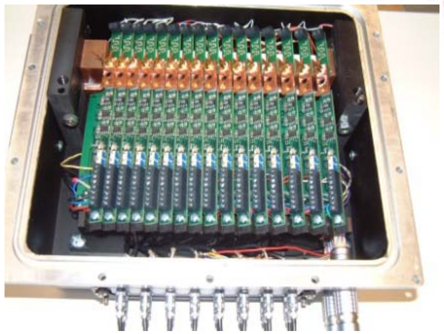
Observation system optimized for light intensity (i.e. time resolution):

- Direct imaging optics
- 14 APD detectors, 500 kHz analog BW, 2.5 MHz sampling
- 1.5-5% statistical noise on full bandwidth
- 10-20 % background in Ohmic, ~100% in NBI discharges

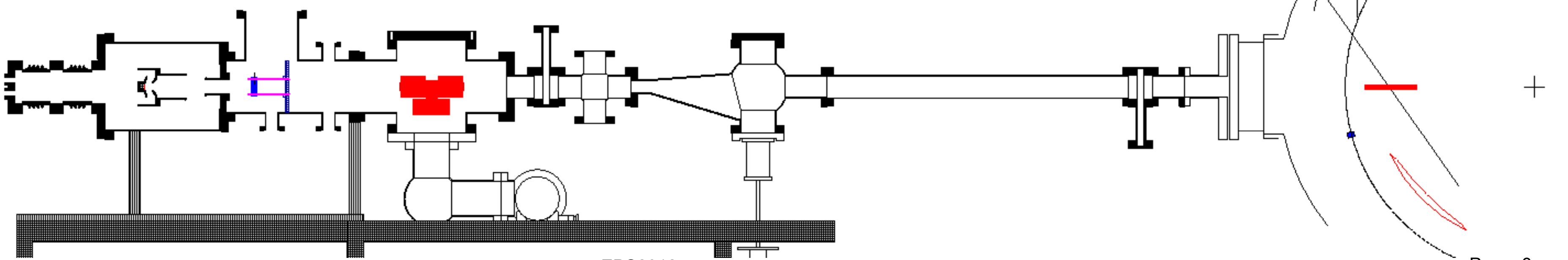
Li-Beam Emission Spectroscopy optics



APD detector system



L-beam injector



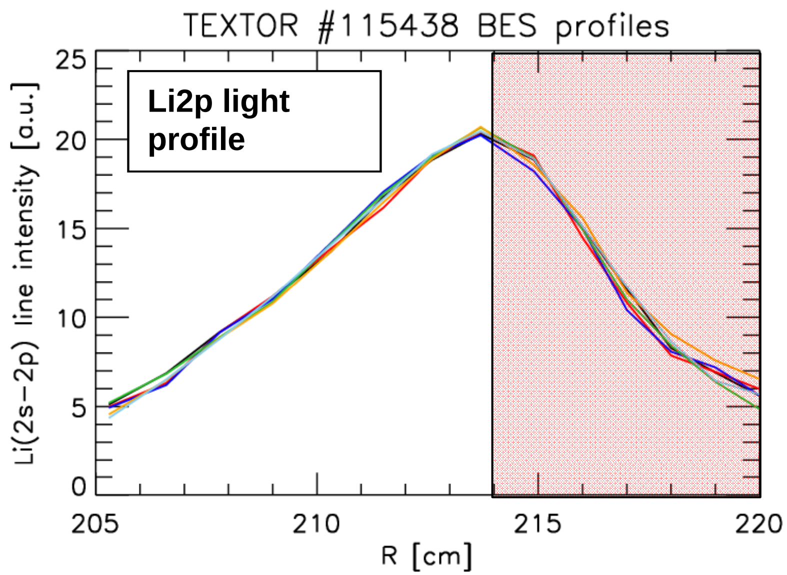
Bayesian method used for electron density calculation

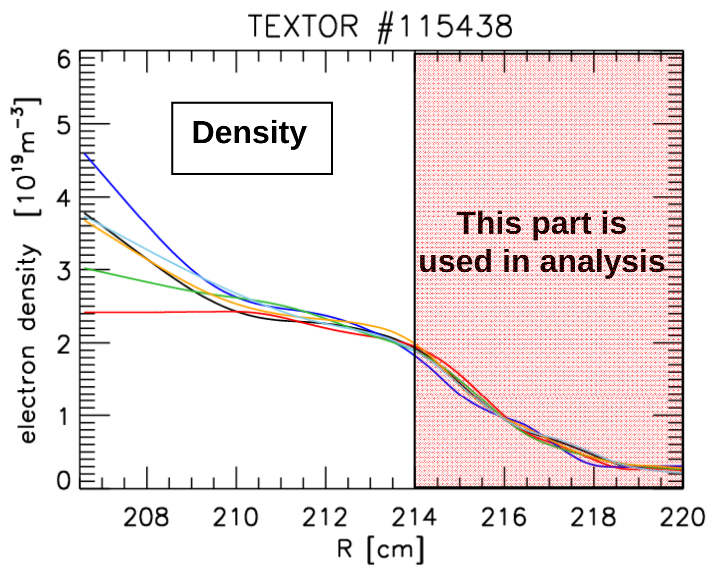
Similar to IPP method described in:
*R. Fischer, et al. PPCF **50** 085009 (2008)*

Based on forward modeling of beam light emission (RENATE 3D beam model)

INPUT
Relatively calibrated light profile
Rough T_e, Z_{eff}, mean ion Z

OUTPUT
Absolute density profile
Li_{2p} population at injection





Errors increase strongly inside maximum of light profile
→ density used only up to maximum of light
(However, full profile is needed for reconstruction)

At edge Li-beam signal is nearly proportional to density:
Statistical analysis (turbulence, ELMs...) are done with Li-beam signals

Fast beam manipulation schemes

Li-BES is the most suitable diagnostic for edge density measurement in L-H transition and ELM studies

- Provides continuous signal with good time resolution
- Pedestal shape and inter-ELM pedestal recovery resolved on ASDEX Upgrade (< 100 μs time resolution)

However, low light level and strong background modulation during ELM is a problem

*R. Fischer, et al. PPCF **50** 085009 (2008)*
*E. Wolfrum, et al. PPCF **51** 124057 (2009)*
*A Burckhart, et al. PPCF **52** 105010 (2010)*

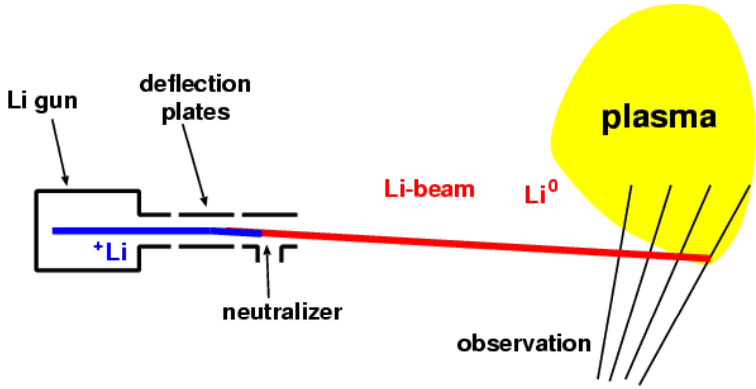
Solution: fast beam chopping + good signal quality

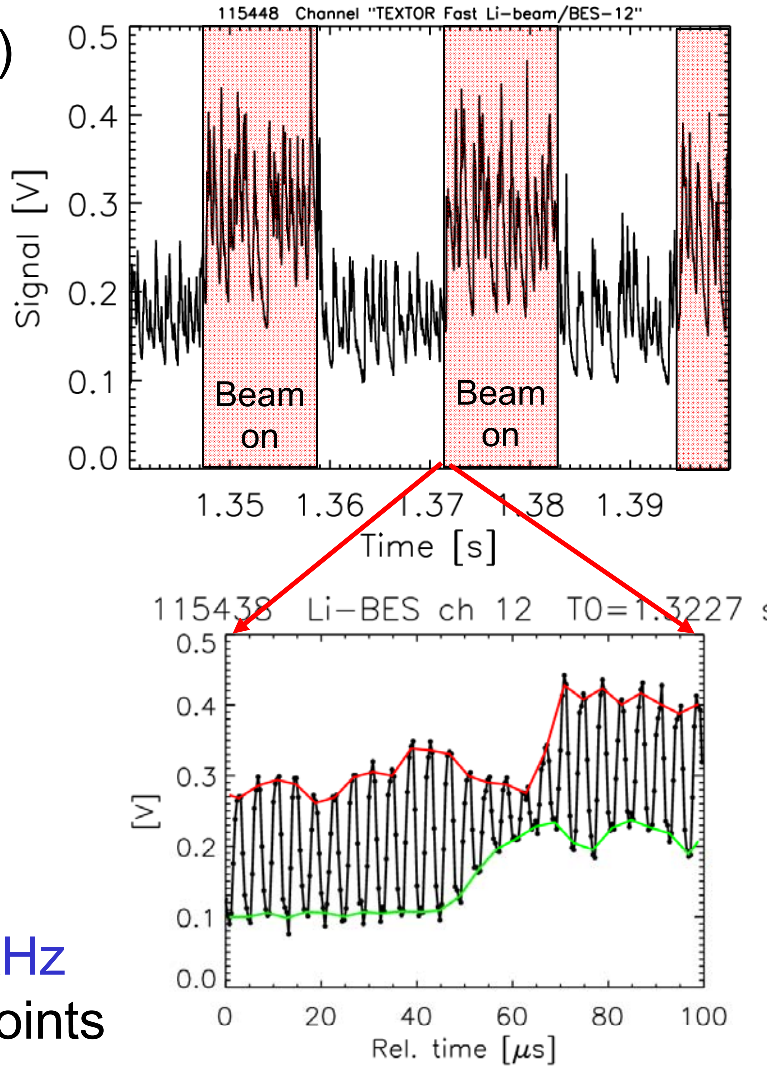
Up to 250 kHz is possible on TEXTOR

→Background corrected Li-beam signal with 4-6 μs time resolution

Fast beam chopping-hopping scheme

*S. Zoletnik, et al. RSI **76** 073504 (2005)*





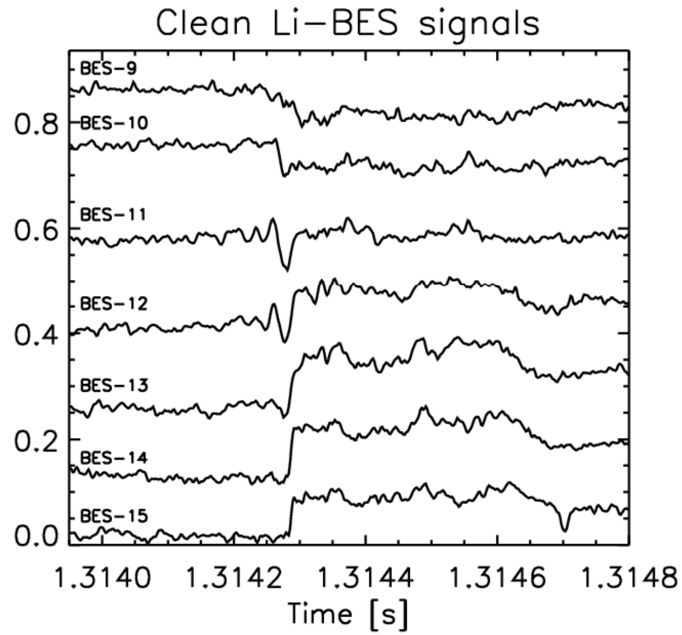
Fast beam chopping signal, virtual background and beam+background signals

Additional possibility: Poloidal beam hopping with 400 kHz

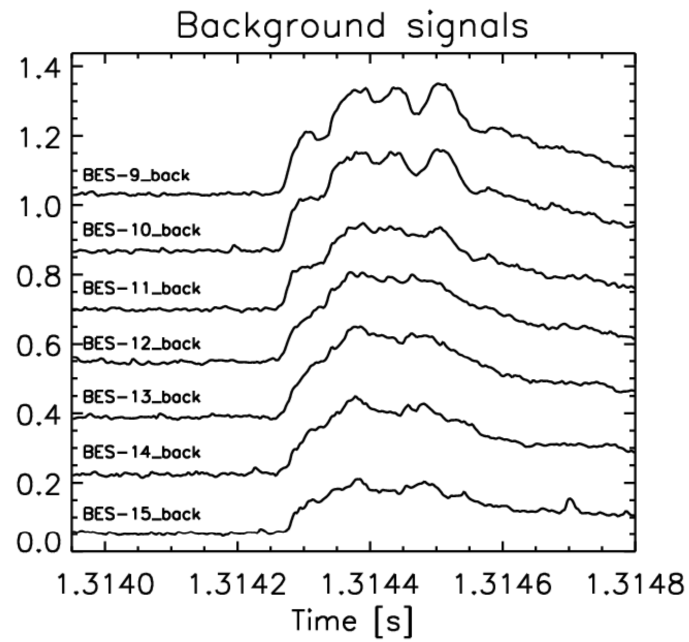
- Two poloidally offset rows (1-2 cm) of measurement points
- Possibility for measuring poloidal structure

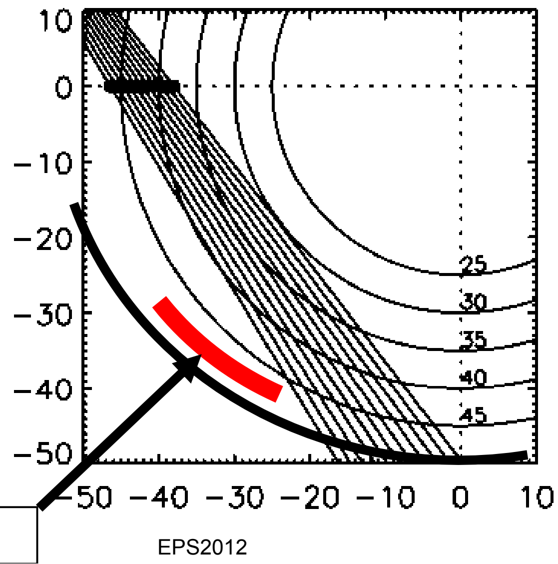
Although background light intensity is high and strongly changing separation of Li-BES from background is possible

→ 14 clean Li-beam and 14 background signals with 4-6 microsec resolution from fast chopping measurement.



Background signals have similar character for all channels.
Probably originate from plasma lower edge
→ Used as a monitor for strength of plasma-wall interaction

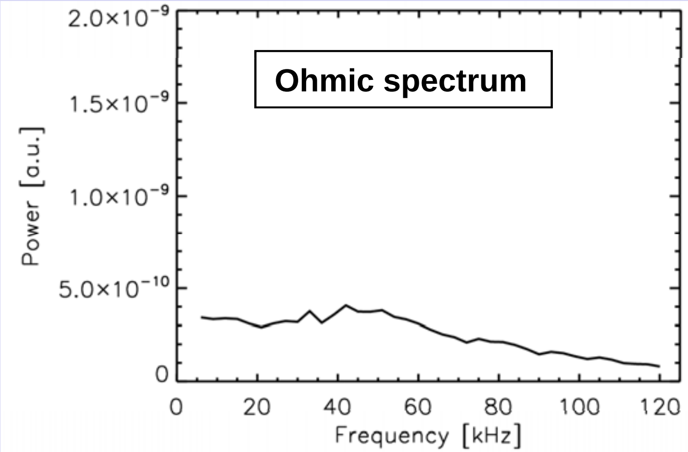




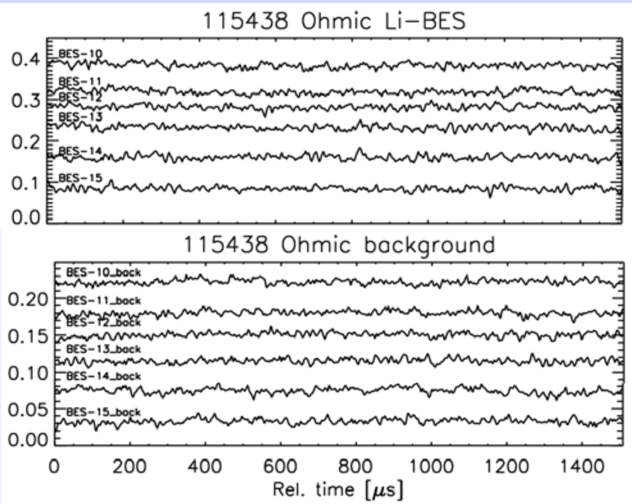
Edge turbulence in Ohmic → NBI-L → NBI-H

Edge turbulence spectrum changes considerably from Ohmic to NBI phase

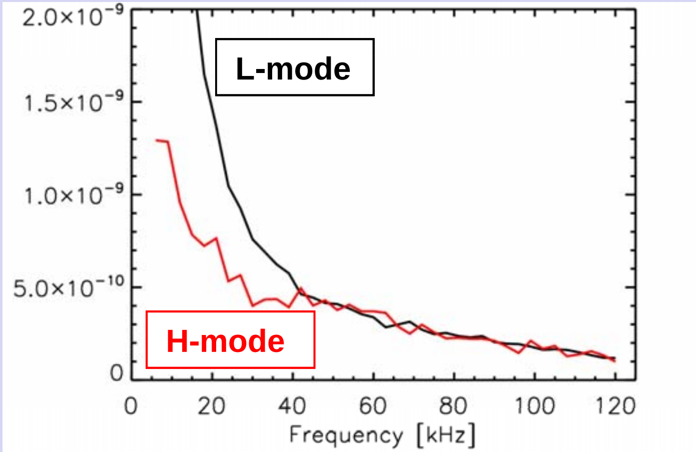
Ohmic

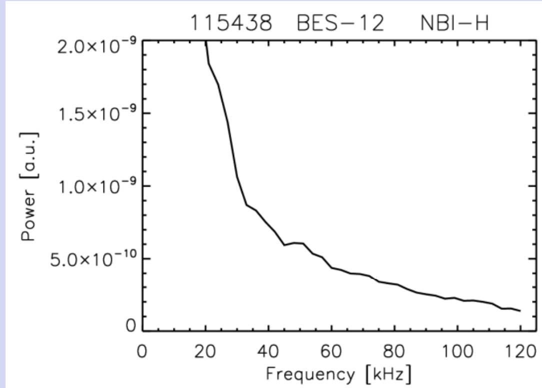


- Broadband turbulence
  + Quasi-coherent mode
- Radial correlation: 2-3 cm
- No correlation with background



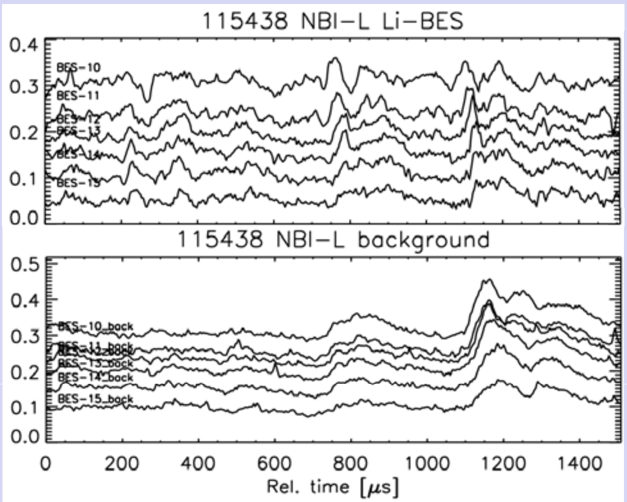
NBI





H-mode spectrum including ELMs is similar to L

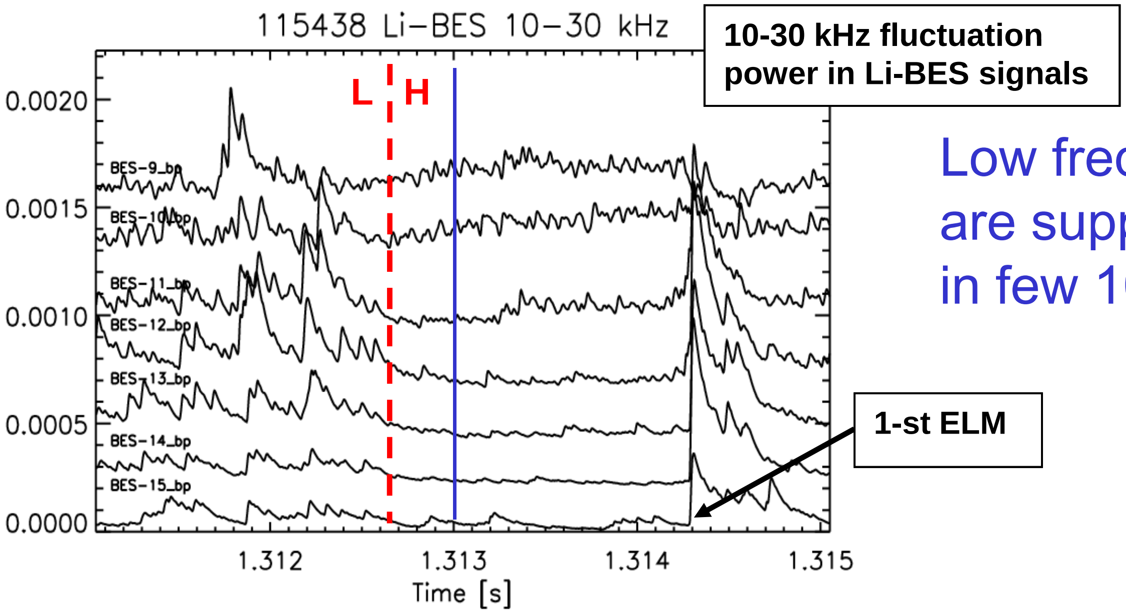
- ELM-like events
- Larger ones modulate background light



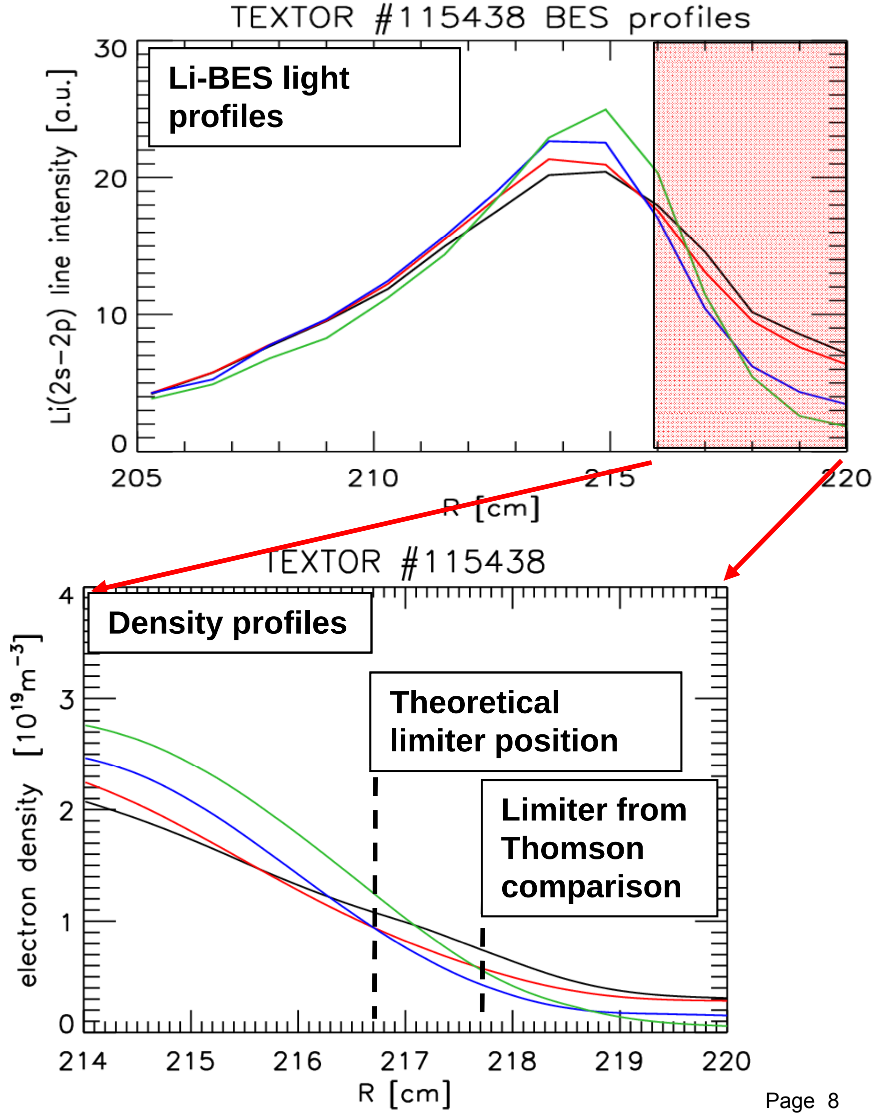
L-H transition:

- ELM-like events disappear
- Low-frequency turbulence suppressed
  → which comes back during ELMs

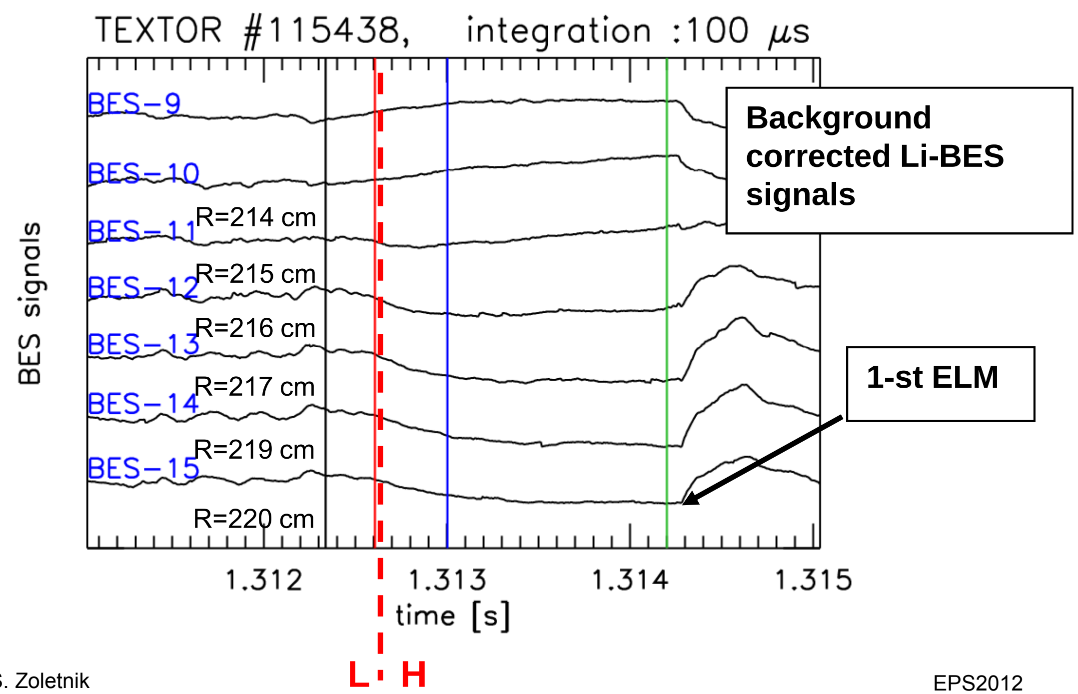
The L-H transition



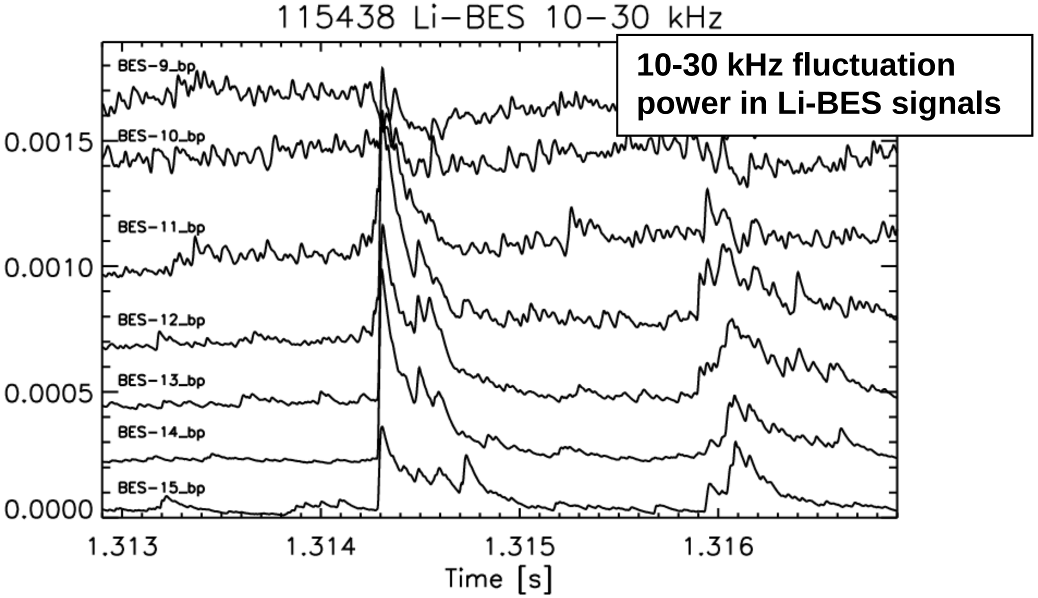
Low frequency (10-30 kHz) fluctuations are suppressed in pedestal in few 100 μs.



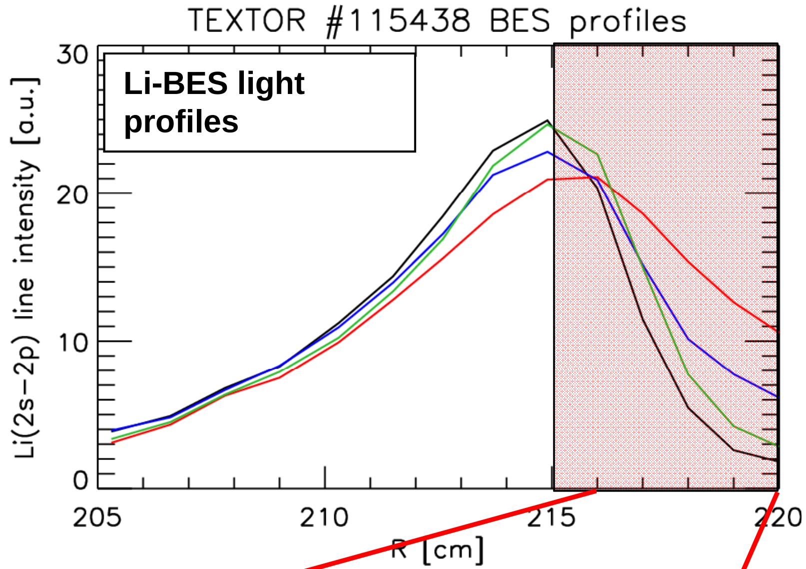
Density pedestal develops on ms timescale



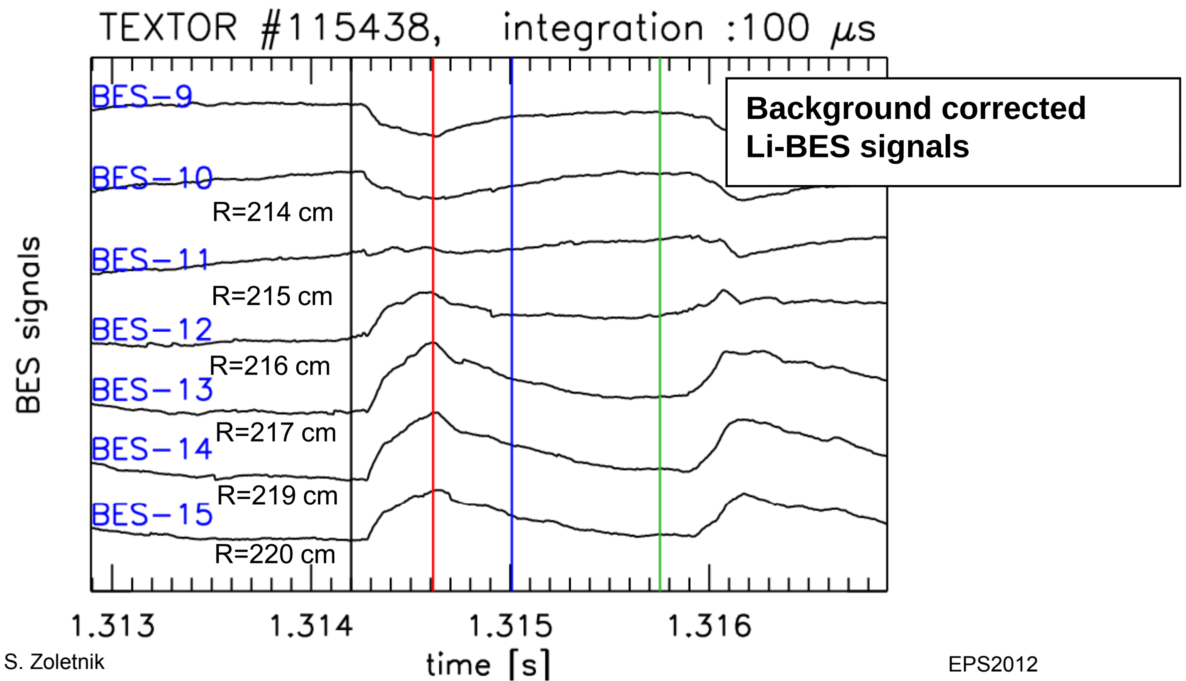
The ELM cycle

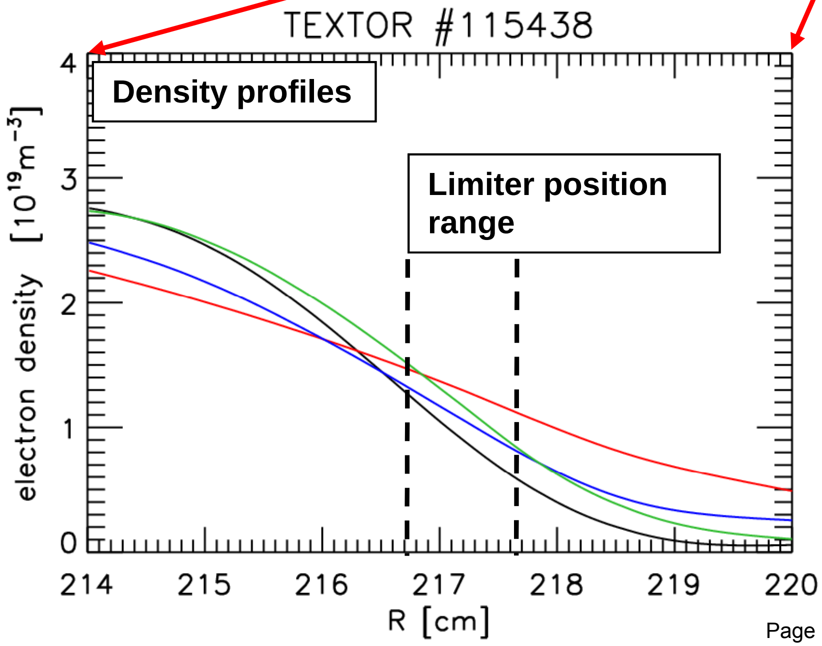


- LF (10-30 kHz) turbulence is high during ELM
- Drops after ELM on few 100 µs.



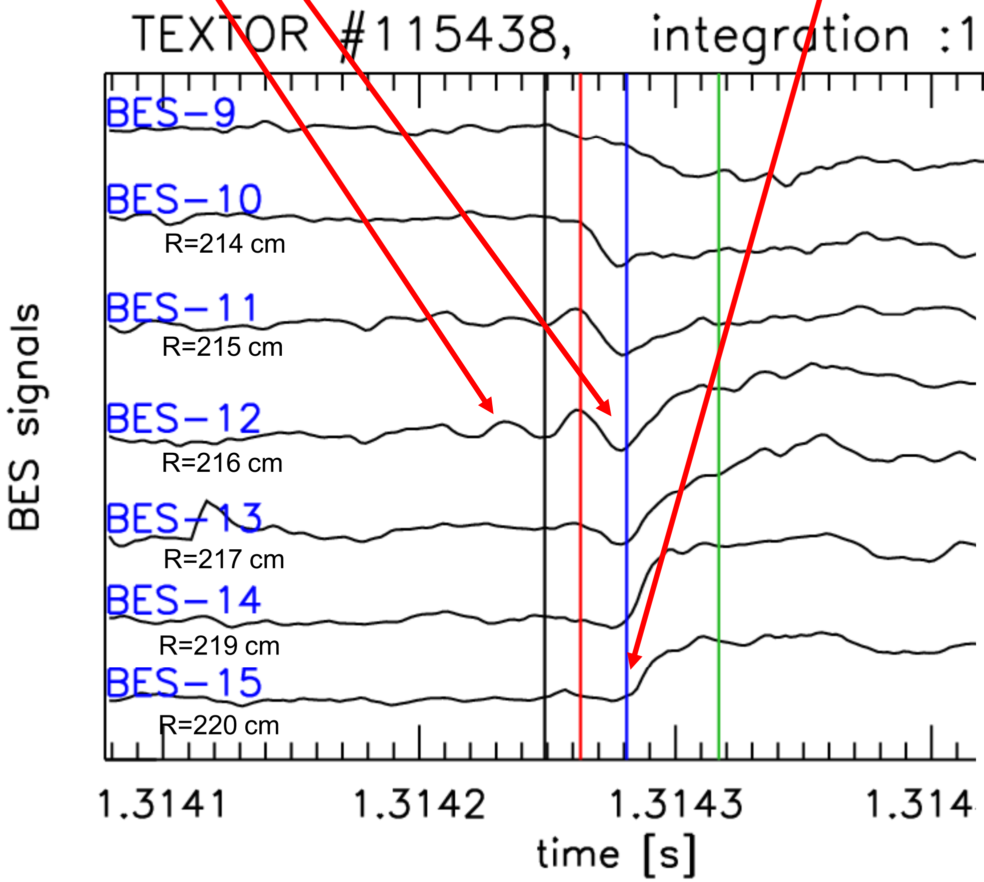
- Density pedestal flattens at ELM
- Recovers on same timescale as L-H transition
- Next ELM starts on fully or partially recovered profile

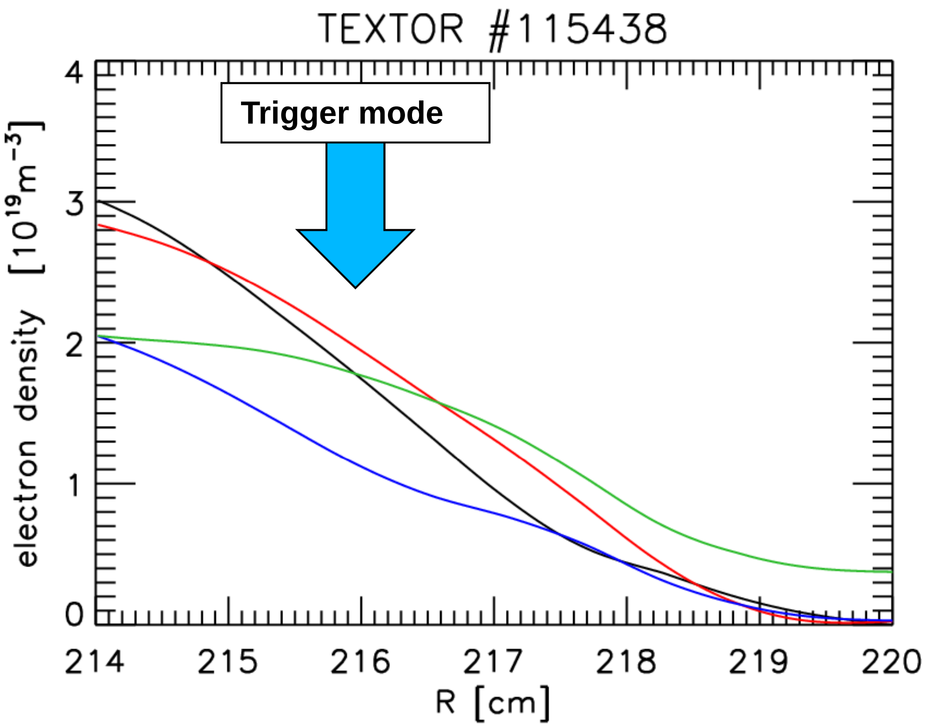




All ELMs are different but some common features are seen:

- First perturbation in density happens at steepest part of pedestal
  - Few period of a 30-50 kHz “trigger mode” is seen often localized to steep part
    - ELM grows out of this precursor
      - Fast increase in density at the edge delayed by 20-50 μs

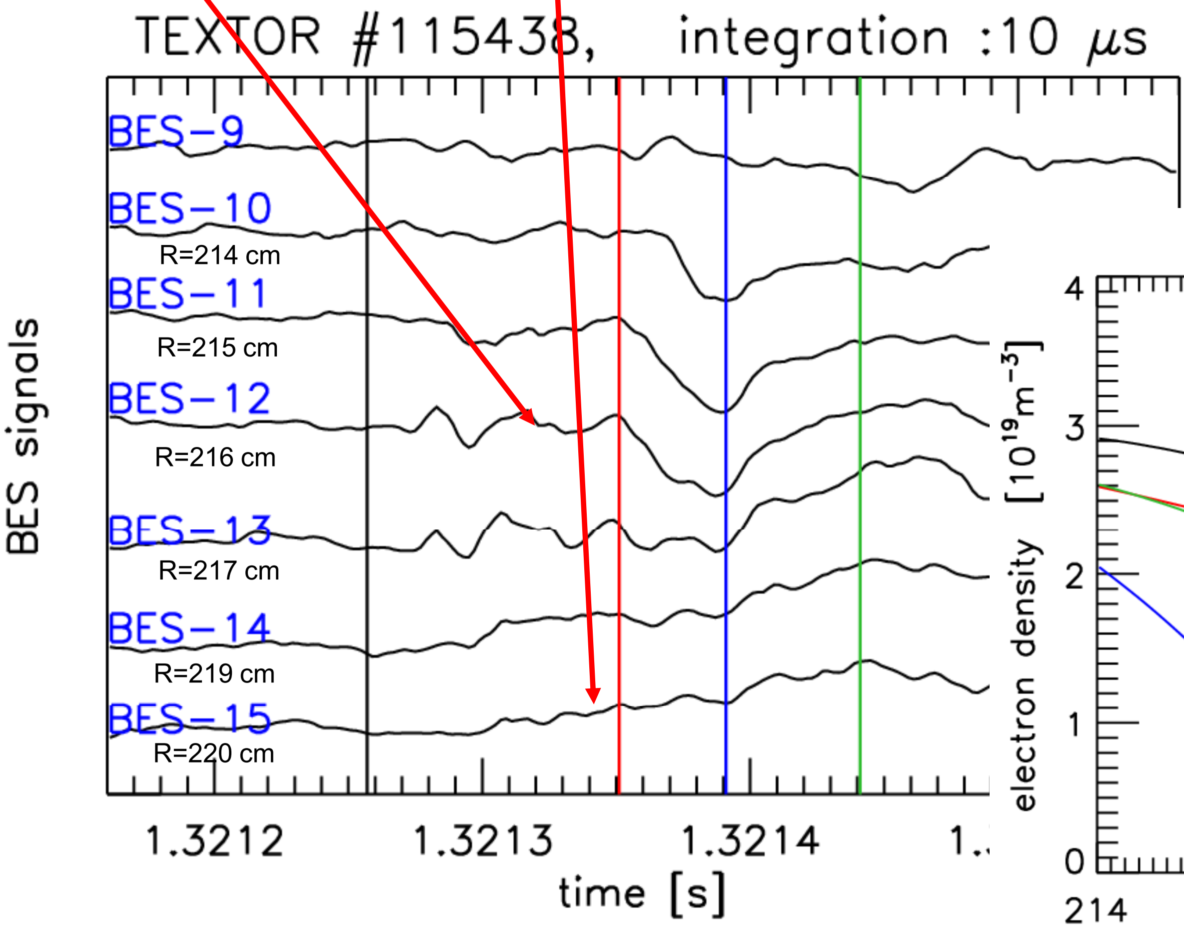


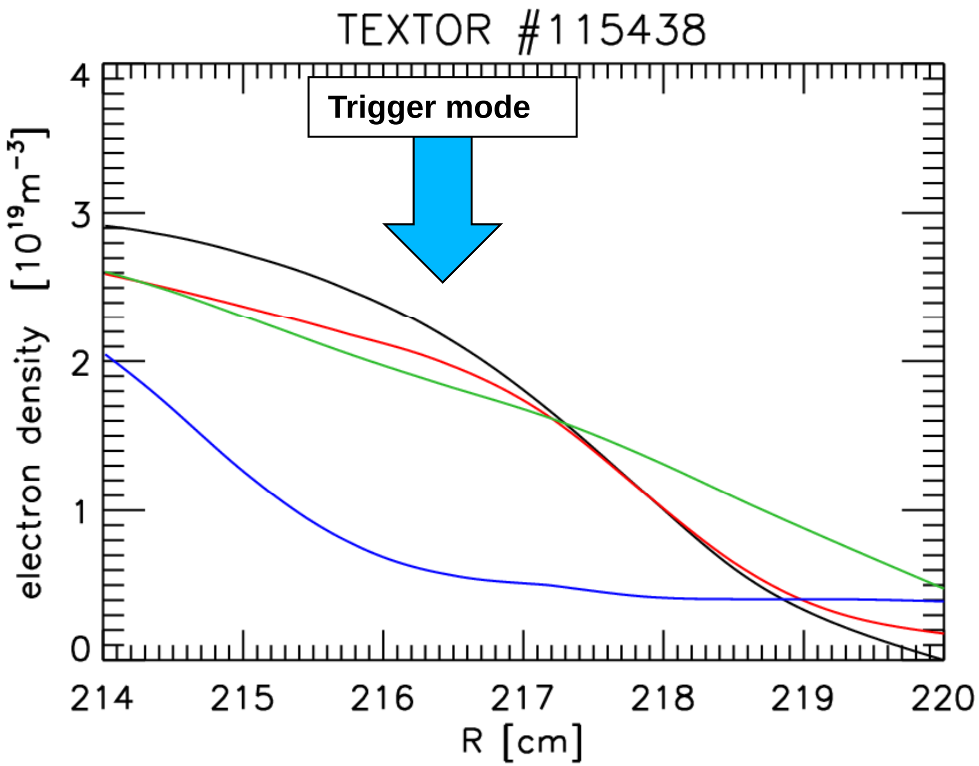


An irregular ELM

Some ELMs have a slow onset

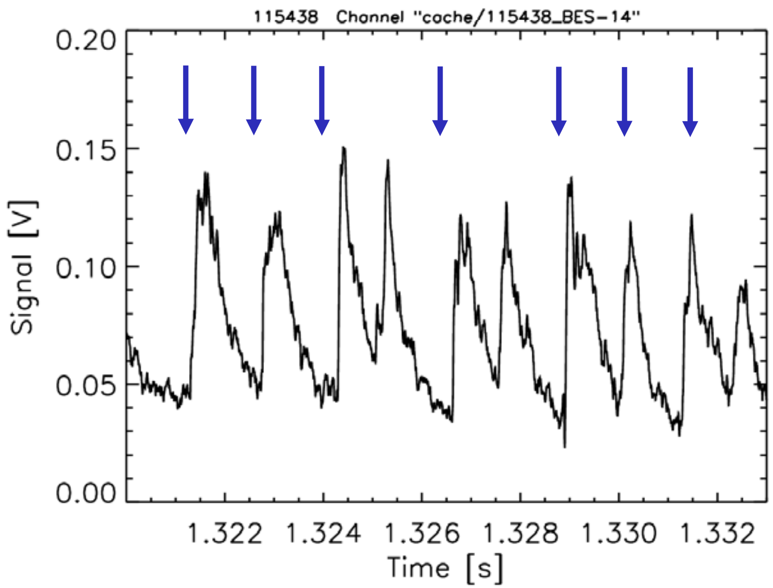
- Trigger mode stops
    - Density increases at edge during 100 μs

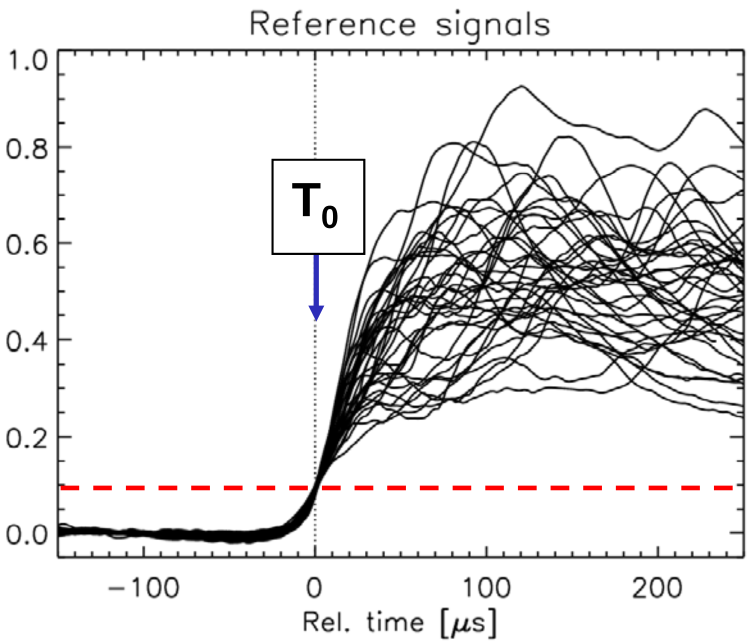




ELM database

1. Hand select ELMs which start from baseline
   (not during decay phase of previous)
2. ELM reference time is determined from sum of all Li-BES background signals:
   T0 is at the time when fixed level is crossed.





Reference signal of 38 ELMs
(Slow ELMs removed)

3. Outliers (slow ELMs) removed by hand
   90 % of ELM background signals follow same trace in first 30-40 microsecond:
   Rest 10% seems to have two-phase trigger: slow start followed by violent phase.

ELM reference time is correct to at least 10 μs for the first 30-40 μs.
Later phase of ELM is strongly variable.

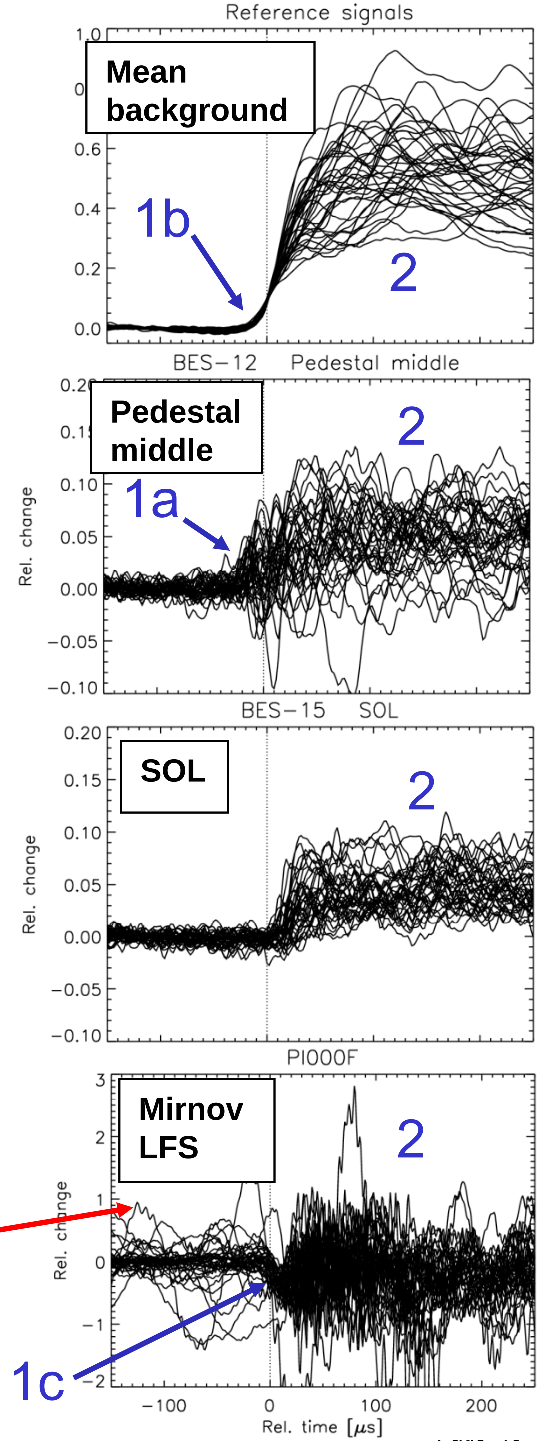
Statistics of ELM onset

Sequence of events:

1. Onset: 20-30 μs
   - 1a. Trigger mode grows at steepest part of pedestal
     Sometimes only in or out movement of profile
     → mode probabaly toroidally localized
   - 1b. Background increases *during* mode growth for all signals
     → edge conditions change
     Not enough time to distribute density on flux surface
     → probably result of hot electrons moved to edge by mode
     → Edge Te increase
   - 1c. Edge poloidal field decreases on LFS
     → Plasma movement or edge current change?

2. Plasma ejection:
   - Density moved radially out several cm *within* 10-20 μs
   - Violent magnetic filed variations
   - Multiple plasma ejections over 200-500 μs

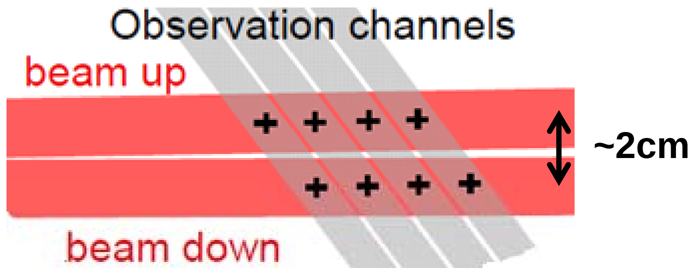
~10 kHz modes often seen before/after ELM.
These seems to be unrelated to the ELM onset.



Poloidal structure of trigger mode

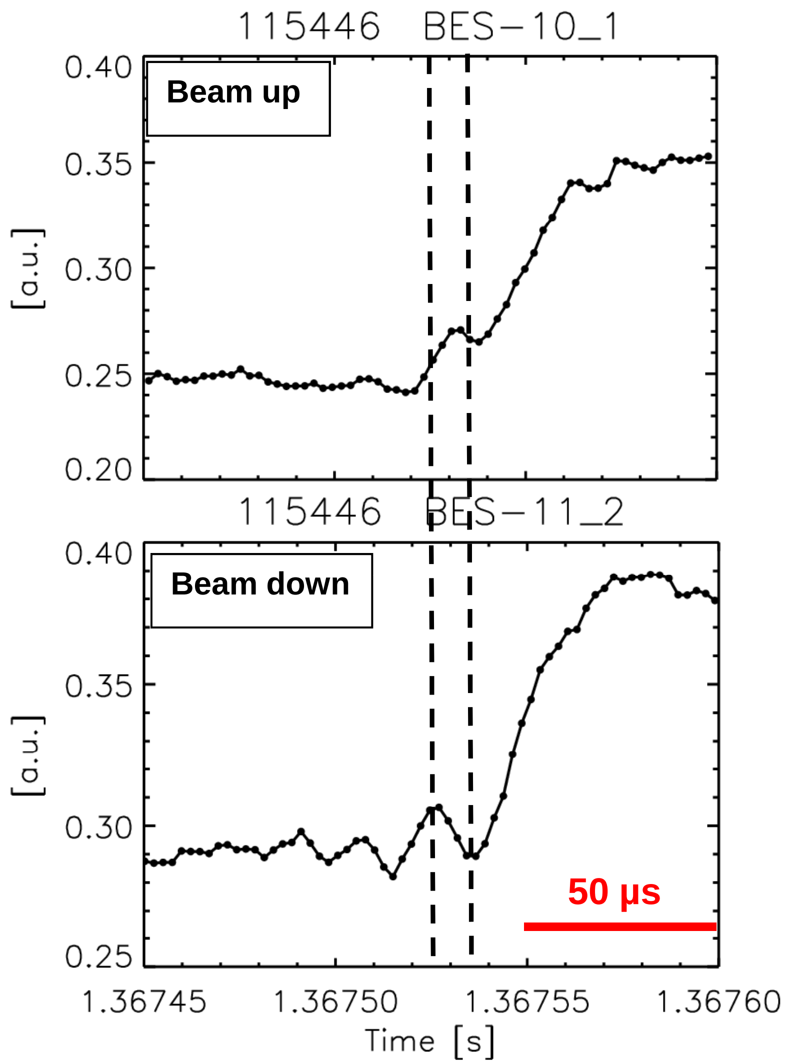
The poloidal structure is measured in fast deflection Li-BES mode

- Two virtual beams with ~2cm separation
- Time resolution: 2.4 μs for both virtual channels
- Trigger mode never seen in background
  → modulation should come from beam signal



Few ELMs studied where mode is clearly seen:

- Phase delay is about 90 degree/2cm
- Wavelength: ~8 cm
- Poloidal mode number: ~30
- Propagation up (e-diam drift), 4 km/s



Conclusions

L-H transition in TEXTOR is related to disappearance of small ELM-like events

- Suppression of 10-30 kHz turbulence in pedestal
- Turbulence suppressed in <1ms
- Density pedestal develops in ~1 ms

ELMs increase 10-30 kHz turbulence

Turbulence and density profile behaviour in ELM recovery is similar to L-H transition

ELMs have 2 phase:

1. Onset: 20-30 μs
2. Plasma ejection: 200-500 μs

ELMs are triggered by growth of 30-50 kHz mode

- At steepest part of density pedestal (= highest pressure gradient)
- m~30
- If not seen ELM starts with fast profile movement
- Seen in part of the cases → possibly toroidally localized
- Grows into the ELM

Trigger mode affects SOL temperature and edge poloidal field during onset phase